




The Value of Geographic Diversity of Wind and Solar: Stochastic Geometry Approach

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WREF 2012: THE VALUE OF GEOGRAPHIC DIVERSITY OF WIND AND SOLAR: STOCHASTIC GEOMETRY APPROACH

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ABSTRACT

The variability of wind and solar power is perceived as a major obstacle in employing otherwise abundant renewable energy resources. Based on the available geographically dispersed data for the WECC U.S. area (excluding Alaska) and eastern U.S., we analyze the extent to which the geographic diversity of these resources can offset their variability.

The set of wind and PV sites that best matches the load with no transmission limitations is determined. For a case with 50% of the load met by wind and solar resources with no curtailments, a geometric model provides a convenient measure for resource variability, and shows the synergy between wind and solar.

NOTATION

G_t – dispatchable generation from conventional sources at hour t

l_t – hourly load (electricity consumption)

P_j – fraction of the maximum potential built capacity at the PV site j

p_{jt} – the input generation that could be produced at hour t by the PV resource at site j

WECC - Western Electric Coordinating Council; here we consider only the continental U.S. territory, excluding Alaska

W_i – fraction of the maximum potential built capacity at the wind site i

w_{it} – the input generation that could be produced at hour t by the wind resource at site i

INTRODUCTION

There are abundant solar and wind resources in the United States – enough to provide more than 10 times the annual U.S. electric load [1]. In spite of this, there are concerns that these technologies cannot supply a significant portion of U.S. generation needs.

Although various technical challenges connected with wind energy [2,3] are being solved, claims have been made that, due to variability, solar and wind power technologies must be heavily, if not completely, backed up with conventional generation capability and/or storage; in other words, the capacity value (i.e. how much conventional generation capacity can be replaced by a unit of renewable generation capacity) of wind and solar is low [4]. We employ new solar and wind resource data at the hourly level that are available for tens of thousands of sites across the country. These data allow us to estimate the value of spreading the deployment of wind and solar plants out to take advantage of the fact that solar and wind availabilities vary geographically, not just temporally.

The integration of significant amounts of wind and solar power in an energy system poses multifaceted challenges [4,5]. The present study focuses on the hour-to-hour variations of demand and generation at tens of thousands of potential wind and solar sites throughout the year in the United States. This paper expands prior findings [6,7] by applying a vector approach to capture important features of the numeric solutions.

APPROACH

The numeric approach is described in details elsewhere [6,7]. We use the renewable energy load matching model (RELM) to determine variability induced limitations on usable wind and solar power. The primary decision variables are where and how much wind (W_i) and photovoltaic (P_j) resource should be built at each wind and PV site (indices i and j respectively). Had we used costs for technologies and fuels, we could have minimized the electricity cost. However, this model gives a robust result without requiring the consideration of future fuel and technology costs.

In the model, wind and solar generation are traded off solely on the basis of how well they meet load; not their relative economics. In our linear program the first constraint is that the load (l_t) is met. The wind and solar sites are selected by the model to minimize the dispatchable generation (G_t). The minimization of the required thermal capacity and allowing no energy losses (curtailments) effectively gives some recognition to the cost of energy:

$$\text{Minimize } \sum_t G_t \quad (1)$$

Subject to

$$l_t = \sum_i W_i * w_{it} + \sum_j P_j * p_{jt} + G_t \quad \text{for all } t \quad (2)$$

$$0 \leq W_i \leq 1 \quad \text{for all } i \quad (3)$$

$$0 \leq P_j \leq 1 \quad \text{for all } j \quad (4)$$

w_{it} is the generation that could be produced at hour t by the wind resource at site i (w_{it} is an input), and

p_{jt} is the generation that could be produced at hour t by the photovoltaic resource at site j (p_{jt} is an input). Both w_{it} and p_{jt} are inputs, thus a perfect forecast throughout the year is assumed.

Expression (1) gives the objective function, (2) sets the condition that all the loads should be met, (3) and (4) set a cap on how much resource can be built at each potential wind or solar site. As a rule, the names for model variables start with a capital letter, while constant parameters begin with a small letter.

INPUT DATA

The wind and PV data that is used for the WECC and a large part of the eastern U.S. have only recently become available. For the wind resource, we are using data developed for the Western Wind and Solar Integration Study (WWSIS) [8][1] and the Eastern Wind Integration and Transmission Study [9]. The distinguishing characteristics of this data is that it includes three years of generation information (2004 – 2006) for 32,000 potential wind sites in the western U.S. and about 6000 potential wind sites in the eastern U.S. in ten minute intervals[2] over the course of each year (http://wind.nrel.gov/Web_nrel). The nominal generation capacity at wind sites in the database is 30 MW for each western U.S. site and varies between 20 and 2000 MW for eastern wind sites.

For the photovoltaic resource, we are using hourly insolation data for the same years for 949 sites in the U.S. found in the National Solar Radiation Data Base [10] and converting that to power generation from a south-oriented PV panel with a 10° tilt using the PVWatts model[3]. The NSRDB does not provide estimates of the maximum amount of PV capacity that could be installed at each site. However to prevent unreasonable overuse of the sites that have generation profiles that best match load profiles, we limited the PV capacity at any single site to 1 GW.

The load data were aggregated from Ventyx's Velocity Suite product, which is based on hourly historical demand for the same years from FERC Form 714 Part III Schedule 2.

VECTOR APPROACH

The vector approach to load matching [7] was introduced to explain geographic diversity effects for quadratic[4] load matching. The idea is to treat hourly generation or load profiles for a year as 8760-dimensional vectors (the number of dimensions equals the number of hours in a year; sub-hourly sampling will require larger number of dimensions). Despite the high dimensionality of load and generation vectors, the number of vectors can be essentially small, which is shown in Fig.1 (from [7]).

Quadratic load matching with just one wind and one PV site, with no constraints on how much capacity can be built on each of them, is a good starting point. Between building wind (43.6° angle[5] with load) and PV (52.2° angle with load) capacity, the model chooses their combination that minimizes the angle between combined (wind plus PV) production and load (37.2°). Generation from a set of wind and PV (thousands of sites from all WECC) sites has less 'variability', which reflects in a smaller angle with load (Fig.1a *vs.* Fig.1b). The synergy between solar and wind can be seen in Fig.1c, which, in a three-dimensional space shows how the combined wind + PV generation can be a closer match for the load than either wind or PV. Using the same type of geometric representation, Fig.1d shows that wind and PV generation

[1] Power output data are also available at http://mercator.nre.gov/wwsi.

[2] We have aggregated the 10 minute data up to hourly data to make the optimization problem manageable and to be consistent with the solar and load data which are available at only the hourly level.

[3] The model is available at http://rredc.nrel.gov/solar/calculators/PVWATTS/version1/.

[4] Quadratic load matching: wind and PV sites are selected to minimize deviations of the combined generation from load on hourly basis.

[5] An angle α between two unit-length vectors a_h and b_h is defined as $\cos(\alpha) = \Sigma_h a_h \cdot b_h$. The angle with load can serve as a measure of resource variability, high α values indicating highly variable resources.

profiles form two separate clusters and that at least semi-quantitatively Fig.1c is a correct representation of wind and solar variability for load matching.

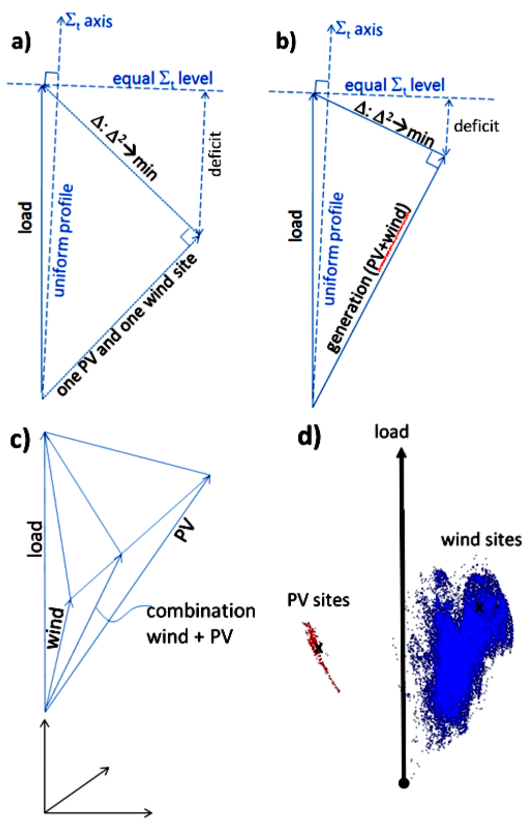

Figure 1 ([7]). Quadratic load matching diagram for the case when a) all generation is concentrated at one PV and one wind site and b) the PV and wind generation sites are selected from all available Western U.S. sites; c) Schematic representation of a three-dimensional diagram shows the combination of wind and PV giving a closer match than either wind or PV; d) projections of wind (blue) and PV (red dots) variable generation profiles.

Fig.1d shows WECC load (black arrow), PV (red dots) and wind (blue dots) generation for the WECC sites: projections of the 8760-dimensional vectors (hourly load or generation profiles) onto three-dimensional space formed by load, average PV and average wind generation vectors. For demonstrative purposes, the nominal capacity for PV generation sites is set to 30 MW (equal to that for the wind sites). Crosses represent PV site #724640 and wind site #10263 that were selected as a separate model case (Fig. 1a). Fig.1d indicates that the wind sites offer a larger diversity of generation profiles than the PV sites.

LINEAR LOAD MATCHING

Many electric sector models (such as Plexos, ReEDS) use linear programming. Linear models require significantly less computation time which in turn allows including more details in the model. In this paper, the vector approach to load matching is applied to a linear model (expressions 1-4).

Table 1 compares linear load matching for three sets of renewable resources: a) one PV and one wind sites with unlimited generating capacity (virtually concentrating wind and PV resources in one place each), b) all available wind and PV sites from WECC, c) all available wind and PV sites from the continental U.S.

Table 1. Linear load matching with PV and wind resources: a) unlimited capacity PV site #724640 and wind site #10263; b) WECC area load matching with PV and wind resources; c) the model matches the U.S. load with U.S. wind and PV resources.

	a) WECC (one PV+one wind site, unlimited capacity,)	b) WECC (wind+PV)	c) U.S. (wind+PV)
Wind capacity, GW	46	101	609
PV capacity, GW	29	47	278
Dispatchables,[6] % of 2005 load	76%	49%	46%
Load^(wind+PV production) angle, °	39°	23°	20°
Dispatchables.^load angle, °	20°	22°	22°

For the cases presented in the table, the dispatchables (vector) closes the balance between production and load. The angle between dispatchables and generation is no longer close to 90° as in the quadratic load matching (because it is no longer the length of the vector being

[6] Share of dispatchables used to meet 2005 load with no curtailment of PV or wind.

minimized, but the sum of its components). The table shows that the angle between load and dispatchables varies within narrow limits 21°±1° between cases (a), (b) and (c).

Load – production angles are mostly determined by the variability patterns of PV and wind generation. The geographic diversity of WECC and U.S. (b,c) alleviates variability of aggregated wind and PV generation which reflects in smaller (compared to case a) load-production angles. And as in the quadratic solution, the selected combination of wind and PV exhibits a closer load match (and smaller angle with load) than either wind (27.2° for case b) or PV (50.6°, case b).

The triangular diagrams (Fig.2) for load matching with wind, PV and dispatchables differ from quadratic load matching (Fig.1) in what concerns the angle between load and renewable (wind + PV) generation. Cases (b) and (c), involving a large number of generation sites, show close values for the two angles in the table. Thus (because of geometry of the triangle in Fig.2b), the sum of dispatchables are close to the sum of renewable generation, both being close to 50% of the total load. The numeric solution (Table 1) confirms this conclusion.

The geographic distribution of wind and PV sites that minimize the amount of dispatchables with no curtailments is shown on Fig.3

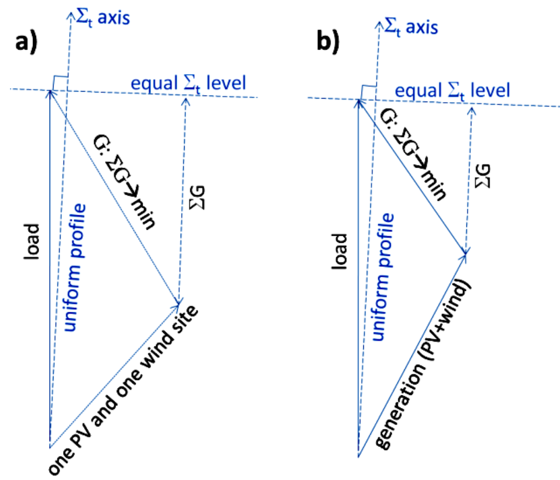

Figure 2. Load matching diagram for a) all generation is concentrated at one PV and one wind site and b) the PV and wind generation is aggregated from Western U.S. sites.

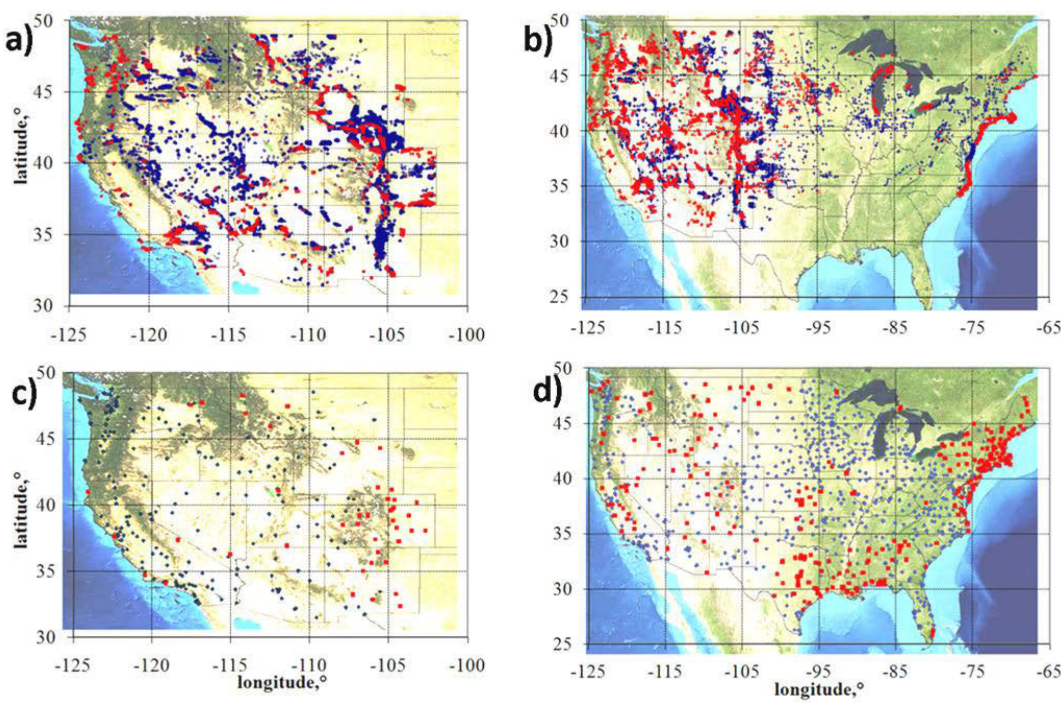

Figure 3. Load matching with diapatchables, wind (a, b) and PV (c, d) buildout for WECC (a, c) and U.S. (b, d). The generation sites that contribute to the optimal solution are shown in red, the remaining sites are shown in blue.

STOCHASTIC GEOMETRY OF LOAD MATCHING

There are several reasons for stochasticity in load matching. First, the number of potential generation sites (tens of thousands) suggests that stochastic methods are relevant. Second, the generation patterns change from year to year and Fig.1d does not exactly replicate in other years.[7] The third reason deals with the geometry of multidimensional figures. In our case, this is the shape described by the condition

$$\sum_t G_t \leq \text{const} \quad (5)$$

which for non-negative G_t is a 8760-dimensional pyramid, its apex is the point Gt=0 for all t and its base is the 8759-dimensional plane defined by equality (5). It is an unimaginably complex shape, although the fact that the angle between load and dispatchables is almost constant (Table 1) suggests that some simple rules apply.

With respect to load matching (1-4), the pyramid should be placed with its apex at the tip of the load vector (Fig.2b) with dispatchable generation G_t representing a pyramid side (the same vector G_t is a side of the triangle). The angle between load and dispatchable generation (that establishes the fraction of wind and solar in the mix) is determined by pyramid properties. Without going into details, for a 8760-dimensional multidimensional pyramid, this angle can range between 1° and almost 90°. The variability of wind and solar, however, narrows down this range to almost a fixed number. Fig.4 shows the distribution of computed distances from the center of pyramid base to the base edge while randomly picking the direction within the base plane. The direction from the origin to each dot on the graph represents the projection of the randomly selected 8759-dimensional direction onto the 2-dimensional picture, while the distance to the base edge (represented by the origin on the graph) is preserved.[8]

It is a property of multidimensional pyramids: most of the base edge-points are located at approximately the same distance from the base center. This distance corresponds to a 30° angle between the uniform profile[9] and the dispatchables vector G_t. When discounted for the angle between load and the uniform profile (9°), it comes close to values found in Table 1. Random variability of wind (and, to some extent, solar) generation in effect randomizes the sampling of the edge-points, and makes stochastic properties of the multidimensional shapes relevant to the solution of the linear optimization problem.

This is a significant simplification of an otherwise complex geometry and makes possible (in the future) the application of stochastic geometry methods to more detailed and realistic load-matching scenarios (including energy storage, curtailments, transmission lines).

There is an immediate practical consequence from the above property of multidimensional pyramids. The angle between the uniform profile and dispatchables does not depend on the number of dimensions (as long as the number is large). Hence, when analyzing load matching at sub-hourly level, the properties of the solution will change only if there are significant sub-hourly variations in wind and/or PV generation profiles, i.e. if PV + wind production angle with load is affected.

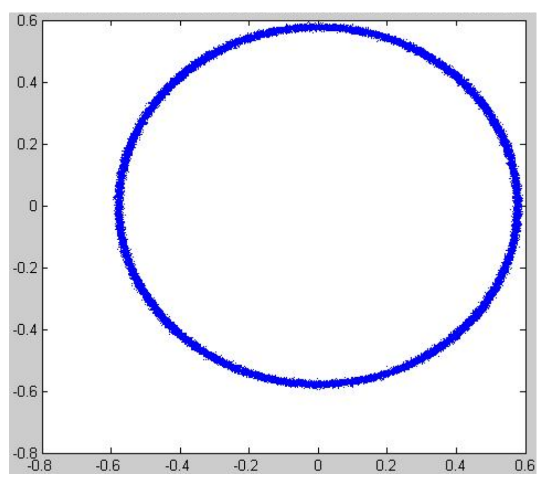

Figure 4. Equidistant projection of pyramid base edge-points on an arbitrarily selected plane. 60,000 randomly selected edge-points are shown.

CONCLUSIONS

The renewable energy load matching (RELM) model is applied to analyze the practical limits of

[7] Direct comparison of 2005 load matching results with 2006 suggests that year-to-year changes are small [6].

[8] For brevity, we'll call this projection equidistant, because it keeps the distance from the projected point to a chosen point (in our case it is the mid-point of the pyramid base).

[9] A constant, not varying with time, profile.

using wind and solar to meet electricity demand in the U.S.

A geometric approach is developed to explain the geographic distribution of the generation sites that best match the load.

Stochastic geometry of multidimensional shapes dictates important properties of load matching solutions.

ACKNOWLEDGEMENTS
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REFERENCES

[1] U.S. Department of Energy: Energy Efficiency and Renewable Energy. 20% Wind energy by 2030; Increasing wind energy's contribution to U.S. electricity supply. DOE/GO – 102008-2567, Washington, D.C.; July 2008.

[2] Thresher R, Robinson M, Veers P. The status and future of wind energy technology. AIP Conference Proceedings 2008;1044(1):340-59.

[3] Joselin Herbert GM, Iniyan S, Sreevalsan E, Rajapandian S. A review of wind energy technologies. Renewable and Sustainable Energy Reviews 2007;11(6):1117-45.

[4] Milligan M, Ela E, Hodge B-M, Kirby B, Lew D, Clark C, DeCesaro J, Lynn K. Cost-causation and integration cost analysis for variable generation. Technical report NREL/TP-5500-51860; June 2011.

[5] Lund H. Large-scale integration of wind power into different energy systems. Energy 2005;30(13):2402-12.

[6] Short W, Diakov V. Matching Western U.S. electricity consumption with wind and solar resources. Wind Energy 2012; in print.

[7] Diakov V, Short W. The value of geographic diversity of wind and solar: a vector analysis. International Mechanical Engineering Conference and Exhibit, paper #63880; Denver, CO; November 2011.

[8] Potter CW, Lew D, McCaa J, Cheng S, Eichelberger S, Grimit E. Creating the dataset for the western wind and solar integration study (U.S.A.). Wind Engineering 2008;32(4):325-338.

[9] EnerNex Corp. Eastern wind integration and transmission study. Subcontract report NREL/SR-5500-47-86. February 2011.

[10] Wilcox S, Anderberg M, George R, Marion W, Myers D, Renne D, Lott N, Whitehurst T, Beckman W, Gueymard C, Perez R, Stackhouse P, Vignola F. Completing production of the updated National Solar Radiation Database for the United States. NREL Rep. CP-581-41511, July 2007.